The effect of terrain-depicting primary-flight-display backgrounds and guidance cues on pilot recoveries from unknown attitudes

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A study was conducted to evaluate the effects of primary flight display (PFD) terrain depictions on pilots' performance of recoveries from unknown attitudes. Forty pilots participated in the study, each group of eight using a different display format. The five conditions consisted of combinations of terrain depiction (none, full-color terrain, brown terrain) and guidance indications (pitch and roll arrows). Participants flew baseline trials in the Advanced General Aviation Research Simulator using a common electronic attitude indicator and then performed recoveries from unknown attitudes (UARs) using one of the PFD formats. Performance measures included initial response time, total recovery time, primary reversals, and secondary reversals. No significant effects of the primary independent variables were found on any of the performance measures. Posttest interviews indicated the participants preferred the directional-arrow indicators and had no preference for or against the presence of terrain depictions during UARs, focusing primarily on the zero-pitch line as a reference. It was concluded that the specific terrain representations examined did not pose a hazard to the identification of and recovery from unknown attitudes as long as a zero-pitch line of sufficient contrast (white with black borders) to all backgrounds was present.

BACKGROUND

Electronic Flight Instrumentation Systems (EFIS) are becoming more available daily, and a major component of this type of system is the Primary Flight Display (PFD). While PFDs initially depicted attitude and flight-guidance information, they evolved to include forward-looking perspective-views of both guidance information (Beringer, 2000) and of the outside world (Wickens, Haskell, and Hart, 1989; Alter, Barrows, Jennings, and Powell, 2000), often generated from terrain databases. This type of display is presently appearing in systems submitted for certification in general aviation (GA) aircraft, and a number of questions have been raised regarding the effects of various design features on different aspects of pilot performance. In lieu of empirical data on the effects of manipulations of specific design parameters, certifiers have had to rely upon general guidelines and often to adopt very conservative criteria for the certification and use of these particular displays.

Some data have become available, relevant to the GA environment, that may be useful for determining what the allowable range of variation in design parameters can be. The parameters that seem to be of present interest include the following: size of the display, angular representation of the outside world (field of view), display resolution, terrain-feature resolution, use of color, style of terrain representation, definition of display clutter, and effects of the above on the performance of both routine and non-routine flight tasks.

A series of studies were performed at the NASA Langely Research Center examining the use of various terrain representations and pilot preferences for various fields of view and styles of depiction (Prinzel, Hughes, Arthur, et. al., 2003; Arthur, Prinzel, Kramer, Parrish, and Bailey, 2004). Some agreement was found with previous studies concerning preference for field of view (30 degrees), and some assessment was made of pilot navigation performance and some basic precision maneuvers, concluding that fewer errors were committed and terrain awareness was enhanced with the displays. One issue that was not addressed, however, was the recovery from unknown or unusual attitudes. This specific concern was addressed in one certification process by requiring that the terrain depiction be removed from the PFD when the aircraft exceeded certain pitch or roll criteria because of a concern that the presence of the terrain might cause confusion or somehow interfere with a successful recovery. However, there were no empirical data to indicate what role, positive or negative, the terrain depiction might play in the recoveries.

Thus, a study was conducted to examine how various forms of terrain depiction might either impede or enhance recoveries from unknown attitudes, including the display content (type of terrain; flat, mountainous) at the time of the recovery as well as the possible ameliorating effect of providing recovery guidance arrows (Gershzohn, 2001). Questions of specific interest were if pilots would recover to the terrain horizon rather than the zero-pitch line if the two were different, if this behavior (if observed) could be ameliorated by positive guidance cues, and if the coloration of the terrain presentation had an effect upon performance.

METHOD

Experimental Display Formats

Forty pilots participated in the study, each group of eight using a different display format. The five conditions consisted of combinations of terrain depiction (none, full-color terrain, brown terrain) and guidance indications (pitch and roll arrows). The no-terrain display consisted of a traditional attitude indicator (blue sky, brown ground) with airspeed, altitude and vertical speed presented in tape format along the left and right edges of the display with a compass card at the bottom of the display.

The second display was identical to the first, but had guidance arrows for pitch and roll recovery. Pitch arrows were linear (Figure 1) and appeared when the aircraft attitude was greater than 13 degrees up or down and disappeared when the aircraft was within 5 degrees of zero pitch, pointing from the aircraft symbol to the horizon. Roll arrows (Figure 2) were curvilinear (arc form) and appeared when the aircraft exceeded 25 degrees of bank and disappeared when the aircraft was within 10 degrees of zero bank, pointing from the plane of the wings to the horizon line. For pitch-down attitudes, the roll-command arrow took precedence over the pitch-command arrow. For pitch-up attitudes, the priority was reversed.

The third display was similar to the first except that the brown portion of the display was replaced with photo-realistic (full-color) terrain (this terrain format is shown in both Figures 1 and 2). The terrain was generated using variable-sized polygons which had photo-realistic texture applied to them to create the out-the-window scene. This is somewhat different from some other terrain-creation methods seen on other terrain-depicting displays where equal-sized polygons or even squares are used to create the terrain skin and a more generic type of texture is applied.

Figure 1. PFD with pitch-recovery arrow shown.

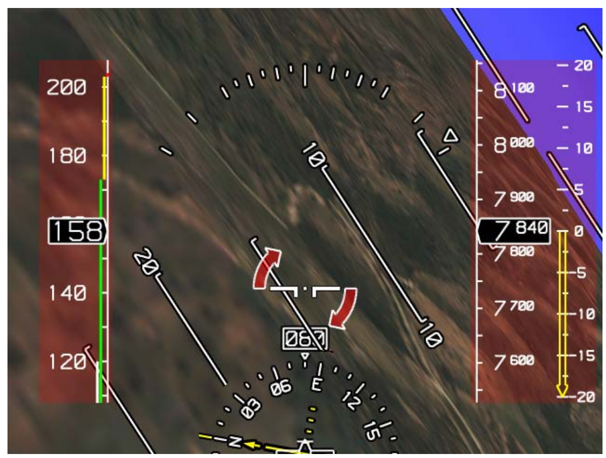

Figure 2. PFD with roll-recovery arrows shown.

The fourth display was the same as the third display, but it included the guidance arrows. The final display was similar to the first display, but the “ground” or brown portion of the display was replaced with brown (polygon-based) terrain imagery. The variable-sized polygon structure imparted more apparent texture to this uniform-brown depiction then one sees in brown-only depictions that use a uniformly sized polygon or square as the basis for terrain-contour construction. Figures 3 and 4 show similar views of a mountain in the full-color mode (Figure 3) and the brown-only mode (Figure 4) for comparison.

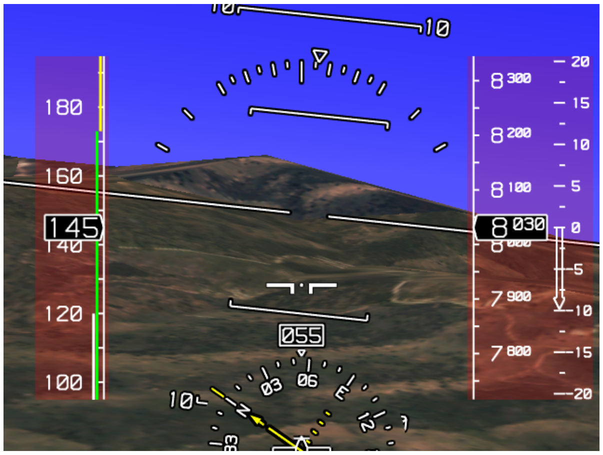

Figure 3. PFD full-color terrain depiction with mountain in view.

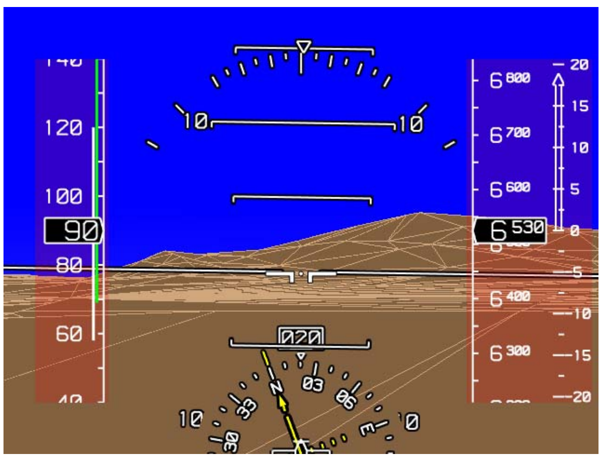

Figure 4. PFD brown-only terrain depiction with mountain in view.

Experimental Design

The design was a two-factor crossed, with terrain background (full-color; present or absent) and guidance arrows (present or absent) as the *independent variables*. The supplemental condition, brown-only terrain, was added after contribution of guidance arrows had been assessed. Dependent variables included initial response time (IRT; time to first control input), total recovery time (TRT), primary control-input reversals, and secondary control-input reversals.

Two *sampling variables* were added to obtain more representative data from across a wider range of display indications. *Terrain depiction at roll-out* was planned using lead headings based upon expected roll-out times (obtained in pretest) and presented terrain either (1) higher than the zero-pitch reference line (mountainous background) or (2) terrain lower than the zero-pitch reference line (level terrain). *Attitude at recovery onset* was also varied so that trials included combinations of pitch (+20, 0, and –15 degrees) and bank (60 degrees left, 0, 60 degrees right) excepting, of course, the zero-zero condition.

Three supplemental trials were also added for approximately the last 7 pilots in each group. For each of these, a 40-degree FOV trial was added, followed by an inverted-recovery trial (by sponsor request), and finally a near-mountains trial where Sandia Peak filled the display up to the 10-degree pitch-up line when the aircraft was approaching at approximately 8000 feet MSL (the terrain horizon was significantly above the zero-pitch line).

Equipment and participants

Data were collected using the Advanced General Aviation Research Simulator (AGARS) in the CAMI Human Factors Research Laboratory. The simulator was configured to represent a Piper Malibu, and the participants all flew in the left seat. The PFD was represented on a flat-panel high-resolution LCD mounted on the instrument panel directly in front of the participant. The PFD was presented at the size of an approximately 7-inch diagonal measurement within a larger hardware-display area, and the image showed approximately 30 horizontal degrees of the outside world. The display layout was similar in many respects to one already certified for GA use. The experimenter-pilot (EP) flew from the right seat with a repeater display of the PFD mounted atop the glare shield. The out-the-window view represented a hard-IFR situation with no environmental visual cues visible in the uniformly gray fields. Performance data were recorded digitally with supplemental audio and visual data recorded on DVD from two video sources (cockpit wide view and PFD inset) and all audio sources (participant, EP, data-collection experimenter).

Participants were 40 general aviation pilots recruited from the local community, 8 assigned to each of the five display conditions. Age and overall flight hours were balanced across groups as participants entered the experiment (not assigned a priori from a known sample). All were at a minimum certified as Private Pilot, while many were instrument rated and a number were flight instructors. Each group had a similar distribution of pilot categories represented.

Procedures/tasks

After completing the informed consent form and filling out a brief pilot-experience questionnaire, participants were briefed concerning the display they would be using and instructed that recoveries would be from unknown attitudes. Their task was to recover to a zero-pitch zero-bank attitude regardless of altitude or airspeed, as the EP would configure the aircraft such that performance was usually within the operating envelope (primary interest was in participant ability to interpret the display and determine when a level attitude had been restored). They were then ushered into the AGARS where they were further familiarized with the display and with the simulator. They then donned a headset and a visor so that direct vision of the display would be obscured when they were in the head-down preparatory position for the recovery.

Each pilot then took off from Albuquerque (ABQ) and climbed out to the north into IFR conditions. All pilots performed 8 warm-up (baseline) recovery maneuvers, using the basic electronic attitude-direction indicator (EADI) on the PFD, to familiarize them with the performance of the AGARS and with the dynamic functioning of the PFD. Each trial began with the participant being instructed to put their head down and take their hands off of the controls. The EP then placed the simulator into the required attitude and heading for that trial, using predetermined airspeed, altitude, and heading criteria that had been rehearsed (the same EP performed all unknown-attitude entries for all participants). The EP gave a preparatory "Ready" about two seconds before handing over the controls, "and" about one second before, and "Go!" at the transfer of controls to the participant. After completing the warm-up trial, the participant flew the simulator back to ABQ and performed a full-stop landing. At this time the display format was changed and the procedure repeated.

Experimental trials consisted of 16 recovery maneuvers, defined by combinations of the sampling variables described earlier, using the PFD that was assigned to the participant. Two different orders of the combinations of sampling variables (attitude at onset and terrain seen at roll-out) were used and balanced across the groups. Accordingly, half of the headings were selected to end the recovery facing mountainous terrain higher than the aircraft altitude and half were selected to end the recovery facing terrain lower than aircraft attitude. Pilot recovery times and initial response times were recorded for each trial. A recovery was considered completed when the aircraft reached ±2.5 degrees of pitch and ±5.0 degrees of bank and was able to maintain those values for 3 seconds, although trials were generally allowed to continue for a few seconds after these criteria had been reached to guarantee stability in the recovery.

The supplemental trials were added to the end of the session. The EP flew the simulator to a designated altitude and starting point near the Sandia Mountains and one recovery was conducted where mountainous terrain occupied a significant portion of the display and the terrain horizon was 10 degrees higher than the zero-pitch line. This was followed by recovery from an inverted attitude with the nose slightly above the horizon and a bank angle of approximately 165 degrees. A final trail was flown with the display FOV changed from 30 to 40 degrees. The participant then flew the simulator back to ABQ for a full-stop landing. Participants completed a posttest set of questionnaires regarding their subjective assessment of the displays (one was also administered after the warm-up trials), went through a posttest interview, and provided both solicited and unsolicited responses/opinions.

RESULTS

Performance Variables

Recovery times. Analysis of recovery times for the baseline trials showed that the groups initially differed in their performance, but were performing equivalently (no significant differences) by the last two trials. This finding suggests that all groups had attained a roughly equal level of performance prior to entering the experimental trials.

Multivariate Analysis of Variance indicated there were no significant differences between the display configurations for either of the response-time variables. Pitch-roll TRTs averaged around 10 seconds, whereas roll-only recoveries averaged about 8.5 seconds. Pitch-only recoveries averaged approximately 8.6 to 9.0 seconds. Univariate analyses were conducted to determine if type of maneuver resulted in any significant differences between display types. Again, no significant differences were found between displays and type of maneuver.

Control reversals. Examination of control reversals, defined as movements in the opposite direction of that required for the recovery, indicated that were only three clearly identifiable primary control reversals in the nearly 800 trials. There were no secondary reversals (initial response in correct direction; subsequent control movement in opposite to input required). Recovery times for the three reversals were not notably different from those of other trials. Thus, reversals did not appear to be a factor regardless of the format of display used.

Supplemental trials. Analyses were conducted for performance variables on each of the three supplemental trials. No significant differences were found for the 40-degree FOV trials, the inverted trials, or the near-mountains trials. Only one of the participants showed any indication of holding the nose of the aircraft above the zero-pitch line in the near-mountain trial rather than completing the recovery.

Questionnaires and Posttest Interviews

Pilots indicated, when interviewed, that they were focusing their attention on the zero-pitch line, which was relatively prominent, and did not regard the terrain depictions, when present, as significant contributors to their recovery task. The directional-guidance arrows produced a positive qualitative response from the participants. Participants also expressed a relatively uniform preference for the terrain-depicting displays in general. A few individuals expressed a preference for the 40-degree FOV, stating that it allowed them to "see more." The one individual who had kept the nose of the simulator slightly higher than zero pitch for the near-mountain trial clarified, in the posttest interview, he had been concerned about the mountain and had kept the nose a little high in preparation for a possible climb over the mountain, having no indeterminacy about the zero-pitch line location.

SUMMARY AND CONCLUSIONS

It appears, for this specific task, that the presence of a zero-pitch line of sufficient contrast (white with black borders) to all backgrounds allows pilots to adequately perform recoveries from unknown attitudes despite the specific format of perspective terrain display used in this experiment. It also appears that the directional-guidance arrows, despite being positively received by the participants and having been demonstrated to be useful in a previous experiment, did not have an appreciable effect on recovery times. The frequency of occurrence of reversals was too low to allow any conclusion to be drawn about the possible effectiveness of guidance arrows in that regard.

Given the previous findings indicating enhanced terrain awareness attributable to terrain depictions combined with the lack of detrimental effects found in this study relative to recoveries from unknown attitudes, there would appear to be fewer significant obstacles to the implementation of this type of PFD for GA use. Caveats to be observed, however, would be that (1) similarly constructed terrain depictions are used, the zero-pitch line is clearly differentiable from the terrain and sky depictions regardless of the type of background and (3) that the direction of off-display pitch-line locations are clearly indicated.

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